Hi-Rel Lead-free Printed Wiring Assemblies

By

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Abstract

The use of lead in electronics has come under increasing scrutiny. Given the trends in both Japan and Europe, it is highly likely that the U.S. will be driven by commercial interests to phase out of lead in electronics usage. This paper presents data collected on a recent NASA project to focus on finding suitable alternatives to eutectic tin-lead solders and solder pastes. The first phase of this project dealt with determining the most feasible candidates to replace tin-lead and to determine suitable processing operations in assemblies printed wiring boards.

Key Words plus Acronyms

- Chlorofluorocarbon (CFC)
- Printed wiring assembly (PWA);
- Printed wiring board (PWB);
- Eutectic tin-lead (Sn 63/Pb 37)
- Lead-free process (LFP);
- Surface mount technology (SMT);
- Solder paste;
- Rosin mildly activated (RMA).

1 Introduction

Lead-containing solder has been used for past 60 years as the principal joining material for Level 2 packaging defined as attaching component level packages to a suitable substrate to produce printed wiring assemblies (PWA's). Generally the solder of choice has been either eutectic tin-lead solder containing 63 wt. percent tin (Sn) and 37 wt. percent lead (Pb) or near-eutectic tin-lead solder containing 60 wt. percent tin and 40 wt. percent lead. Eutectic tin-lead solder has a unique melting point of 183°C (361°F), whereas near-eutectic tin-lead solder melts within the range of 183°-189°C (361°-372°F).

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Tin-lead solder forms stable solder joints capable of operating in a wide variety of service environments. It is easy to use, and because it has a relatively low melting point, rework and repair are also easy. In addition, the reliability of tin-lead solder joints is well understood. Using Coffin-Manson curves and Weibull distribution plots of thermally cycled solder joints, it is possible to estimate the amount of useful life remaining for tin-lead solder joints after exposure to a known number of thermal cycles.

It is widely recognized that the use of lead in electronics accounts for only a very small percentage of lead used worldwide. Possibly only 2-3% of the lead utilized in manufactured products ends up in electronic products. Nevertheless, the fear is that lead-containing electronic products will ultimately find their way into landfills. As a consequence, the lead could be leached out and end up in ground water reservoirs. The issue has now moved out of the technical arena into the political one. It makes very little difference what the technical realities are since they tend to be obscured by political and social perceptions.

In fact, this movement shows the ever-growing importance of what is called Design for the Environment (DFE) and Green Manufacturing. Both emphasize the use of environmentally benign materials so that the environment is impacted as little as possible.

Although there are a number of potential substitutes for tin-lead solder, there is no simple drop-in replacement for this material. All substitutes have properties somewhat divergent from that of tin-lead and will require both process development and validation. In electronics the impact will be felt by bare printed wiring boards, components, and electronic card assemblies. Compared to tin-lead solder, these other solder materials display advantages and drawbacks. This situation is analogous historically to what took place when the search was initiated to find suitable substitutes for chlorofluorocarbons (CFCs) back in the early '90s.

2 Background

Almost all viable candidates have melting points greater than 200°C but below that of pure tin, which has a melting point of 232°C (449°F). About one year ago, NASA funded a project to begin searching for suitable candidates under the aegis of the NASA Electronic Parts and Packaging (NEPP).

Four lead-free solder pastes were selected based on an extensive search of the literature. These are given below in Table 1. Two PWBs per solder type were assembled using the four different solder pastes resulting in total of eight assemblies.

Table 1: Lead-free Solder Alloys for Test

Composition	T_m (°C)	Advantages	Potential Issues
1) Sn96.5Ag3.5 (eutectic)	221	a) Good wetting characteristics and superior joint strength compared to Sn/Pb solder b) Long history of use	a) May exhibit structural weakness at solder connection b) High T_m
2) Sn95.5Ag3.8Cu0.7	217-218	a) Recommended by NEMI b) Virtually no plastic range c) Rapid solidification avoiding formation of cracks d) Formation of intermetallics $Cu6Sn_5$ and Ag_3Sn provide greater strength and fatigue resistance than Sn/Pb solder	a) High T_m
3) Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®)	217-218	a) Addition of Sb improves thermal fatigue b) Solder coating offers flatter pads and uniform coat c) Works well with Ni/Au Ag/Pd and OSP boards d) Sb slightly reduces melting temperature and refines grain structure	a) Sb Trioxide may exhibit toxicity at higher temperatures b) High T_m
4) Sn77.2In20.0Ag2.8 (Indalloy 227®)	175(T_S) - 187(T_L)	a) Compatible T_m to Sn/Pb b) Good ductility, strength and creep resistance c) Low dross in wave solder	a) Supply and cost may be prohibitive factors in its use. b) 118^0 C eutectic point may deteriorate mechanical properties of solder joint c) Large plastic range

3 Objectives

The objectives of the task are three-fold:

1. Ensure that the new lead-free pastes can be successfully assembled. It is still an open issue whether printed wiring boards (PWBs) and components can be successfully processed at the higher process temperatures (30°-35° C greater than for eutectic tin-lead).

2. Based on the results of 1, we will down select from the initial four pastes to two.

3. Assemble four PWBs per paste (2 pastes) and thermal cycle. The exact thermal cycle is still to be determined. Assemble four PWBs with eutectic tin-lead paste as a control lot. There are several types of thermal cycles being used depending upon the product and the industry. These are described in IPC-9701 document.

   Some of them are –
   JPL Cycle: -55° C to 100° C
   Military Cycle: -55° C to 125° C
   Commercial: 0° C to 100° C

   All of the selected pastes have been acquired, and are presently at hand at JPL. In addition, 25 test PWBs along with a number of electronic components with which to assemble the PWBs have all been received.
   In addition, we received 5 lb. of Sn96.5Ag3.5 bar solder to fill a solder pot, and 1 gallon of perfluorinated material for the vapor phase reflow unit to join the components to the PWBs. The vapor phase reflow is a bench-top model for use in this project. Eight PWBs using the four different solder pastes per Table 1 were assembled.

4 Pertinent Process Information

The following JPL process information is pertinent to the discussion:

- Rosin-based fluxes and pastes are used to produce all electronic hardware. Using the terminology of Mil-F-14256, the classification of these products is rosin mildly activated (RMA).
- The solder paste is applied using a semi-automated screen printer ensuring that the paste is deposited in a uniform and consistent manner. Only stainless steel stencils are used in conjunction with a stainless steel squeegee. All boards are visually inspected for proper paste deposition after the stencil operation.
- A laser-based solder paste height and width measurement system is used with a resolution of 0.0001 inch (2.5 μm). This system provides real time information on the uniformity of solder paste deposition. All boards are subjected to this measurement prior to the reflow operation.
- An automated placement machine is used to place parts on the printed wiring board (PWB).
- A batch vapor phase reflow operation was used to create the solder joints of the SMT PWAs. The SMT PWAs are thermally profiled using a M.O.L.E.® A thermocouple was attached to the PWB and to the M.O.L.E. which is a microprocessor-based data logger attached to a computer. Thermal profiling was done to eliminate thermal shock during preheat and reflow. This operation consisted of a vapor phase reflow machine using a constant boiling perfluorocarbon material (under proprietary name Galden® from Ausimont Corp., boiling point 240°C) for soldering the lead-free SMT PWAs. The PWAs were preheated to remove paste volatiles and to initiate the activation stage of the paste. The reflow liquid, since it boils at a constant temperature, minimizes the possibility of overheating the PWAs during reflow and ensures that the vapor blanket performs a uniform and consistent soldering operation.
  For eutectic tin-lead and Indalloy 227, 3M Perfluorocompound FC-5312® with a boiling point of 216°C was used.

5 Assembly Process

Double-sided test PWBs with footprints for various chip components and IC packages, including BGAs, were assembled. Figure 1 shows both sides of PWB. The BGAs were daisy-chained. Various mechanical packages were selected for the test and were acquired. Component package types used were as follows.

1. Chip resistor, 0603 package (24 each per board)
2. Chip resistor, 1206 package (18 each per board)
3. SOT 23 package (2 each per board)
4. SOIC20 package, 50 mil pitch part (2 each per board)
5. PLCC68 package, 50 mil pitch part (1 each per board)
6. QFP100, 25 mil pitch part (1 each per board)
7. QFP208 package, 20 mil pitch part (1 each per board)
8. BGA225 full array package, 1.5 mm ball pitch (1 each per board)
9. BGA352 area array package, 1.27 mm ball pitch (1 each per board)

5.1 Pre-assembly Inspection and Test

Prior to assembly, all the BGA pads on the PWBs were checked to ensure the daisy-chain integrity and in addition all BGA components were checked to ensure the daisy-chain integrity.

All eight PWB's and one sample of each component were tested with scanning acoustic microscope (SAM) to obtain a signature prior to assembly.

5.2 PWB and Component Preparation

All PWBs were cleaned in an Accel centrifugal cleaner using Vigon® A200 chemistry available from Zestron Corp. Viagon chemistry consists of a 20% solution of a proprietary blend of alcoxypropanols and amine compounds in DI water with 1% corrosion inhibitor and 0.1% defoamer. The cleaning cycle and its parameters were as follows.

- Purge the wash chamber with nitrogen gas for one minute
- Wash cycle of 5 minutes duration using Vigon A200 solution heated to 50^0 C
- Rinse cycle of 10 minutes duration using DI water heated to 50^0 C
- Dry cycle of 5 minutes duration using air heated to 180^0 C
- Vacuum oven bake cycle for 8 hours at 100^0 C

5.3 Screen printing

PWB's were screen printed with four different pastes per following Table 2

Table 2 Four Pb-free Solder Pastes Used

Item	Paste Type	PWB Serial Number
1	Sn95.5Ag3.8Cu0.7	PWB S/N 001 and 002
2	Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®)	PWB S/N 003 and 004
3	Sn96.5Ag3.5 (eutectic)	PWB S/N 005 and 006
4	Sn77.2In20.0Ag2.8 (Indalloy 227®)	PWB S/N 007 and 008

Printing parameters were as follows.
Stencil Type— Stainless steel with foil thickness of 7 mils;
Squeegee Type —Metal Blade;
Squeegee pressure setting — 5.6 kg;
Squeegee speed — 15 mm per second.

Paste height was measured using 3-D laser based measurement system.
The paste height data of selective pads for each solder paste type is shown in Figure 2.

5.4 Component Placement

Components were placed on side 1 using automated placement machine. A split vision rework system was used for component placement on side 2.

5.5 Solder Paste Reflow

Two types of vapor phase reflow systems were used to reflow the solder pastes. Both consisted of an infrared preheating zone followed by a constant temperature boiling vapor zone.

Pastes 1, 2 and 3 (listed in Table 2) were reflowed using a bench top vapor phase system containing Galden perfluorocarbon material with a boiling point of 240^0 C. Paste 4 was reflowed using a stand-alone system containing 3M perfluorocarbon material with boiling point of 216^0 C.

A thermal profile was generated for each system. Figure 3 shows the one for higher melting point solder paste 1, 2 and 3 per Table 2. The assembly was preheated to approximately 158^0 C at the rate of 0.88^0 C /Second followed by vapor phase reflow. The dwell time above liquidus was 62 seconds.

5.6 Post Reflow Cleaning

All PWAs were cleaned in the centrifugal cleaning system using the cleaning cycle described in section 5.1

5.7 Cleanliness Test

All PWAs were tested for ionic level using an Ionograph 500® tester.
The cleanliness levels recorded by the Ionograph were as follows.

Table 3 Ionic Contamination Levels

PWA S/N	**Solder Paste Type**	**Ionics- μg/in²**
S/N 001	Sn95.5Ag3.8Cu0.7	0.32
S/N 002	Sn95.5Ag3.8Cu0.7	0.33
S/N 003	Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®)	0.05
S/N 004	Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®)	0.05

S/N 005	Sn96.5Ag3.5 (eutectic)	0.26
S/N 006	Sn96.5Ag3.5 (eutectic)	0.19
S/N 007	Sn77.2In20.0Ag2.8 (Indalloy 227®)	1.68
S/N 008	Sn77.2In20.0Ag2.8 (Indalloy 227®)	1.28

All PWAs were baked in a vacuum oven at 70^0 C for 30 minutes.

5.8 Visual Inspection and X-Ray

All PWAs were inspected under a microscope at 12 X magnification. The observations made are listed below.

- The solder flow generally appeared good except that the solder appeared grainier compared to Sn/Pb solder joints.
- The solder joints containing indium were even more grainy than the other three types of joints.
- There was one solder bridge at the corner on S/N and 008

See figures 4, 5, 6, 7 and 8.

5.9 Scanning Acoustic Microscopy

All PWAs were tested with scanning acoustic microscope to reveal the post assembly signature of the boards.
The tests are being conducted and the results are not available at this time.

6 Conclusions

The following conclusions can be drawn.

- No problems were encountered during the printing process with lead free paste. The printing was uniform for all PWBs.
- A longer delay was required for the first three pastes during the reflow process. This was due to the higher melting temperature of the solders.
- Although the solder fillets appeared to be generally good, the solder joint appeared grainier than those formed by Sn63/Pb37 solder.
- The daisy-chain continuity measured after reflow was same as that prior to the reflow, meaning there was no opens after reflow.
- In the upcoming Phase II tests, several PWB assemblies will be built using the lead free pastes and the PWAs will be subjected to thermal cycling and vibration tests.

7 Acknowledgements

The research to investigate lead-free soldering and finding a suitable lead-free candidate to replace eutectic tin-lead was performed at the Surface Mount Technology Laboratory at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

8 References

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2. Karl Seelig and David Suraski. AIM Inc. “An Overview and Comparison of Viable Lead-Free Alloys

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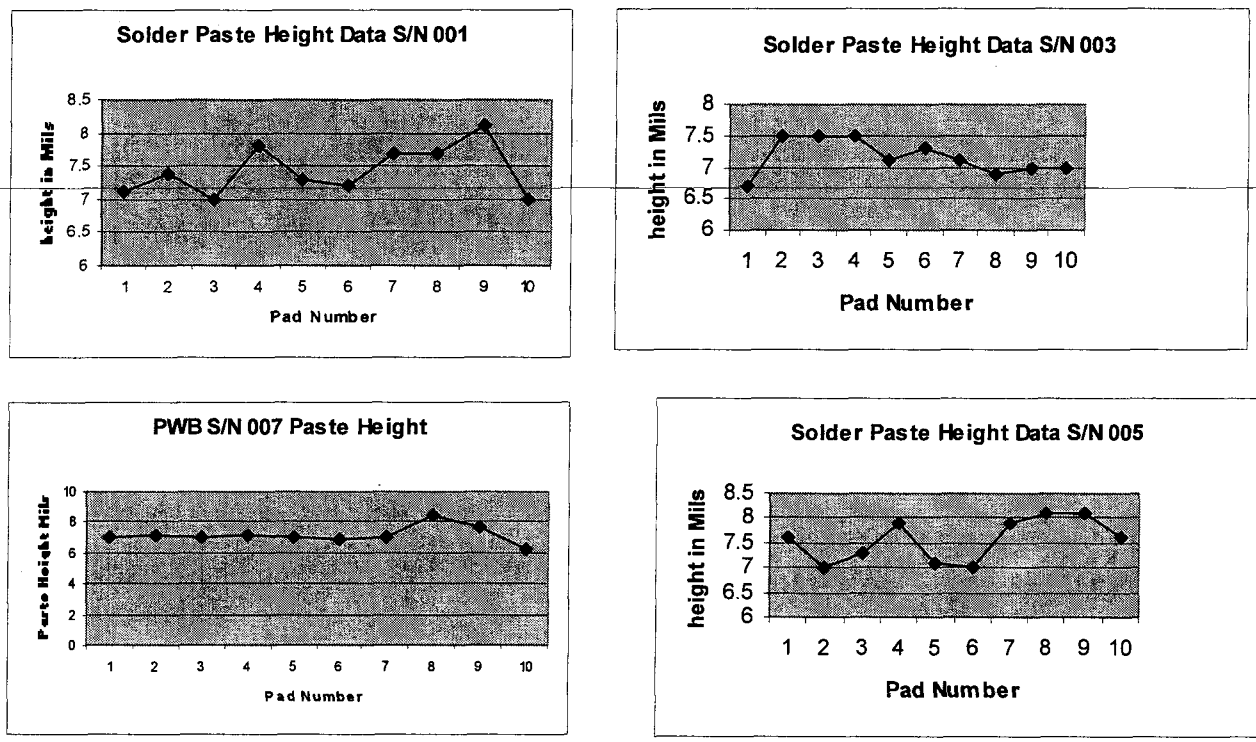
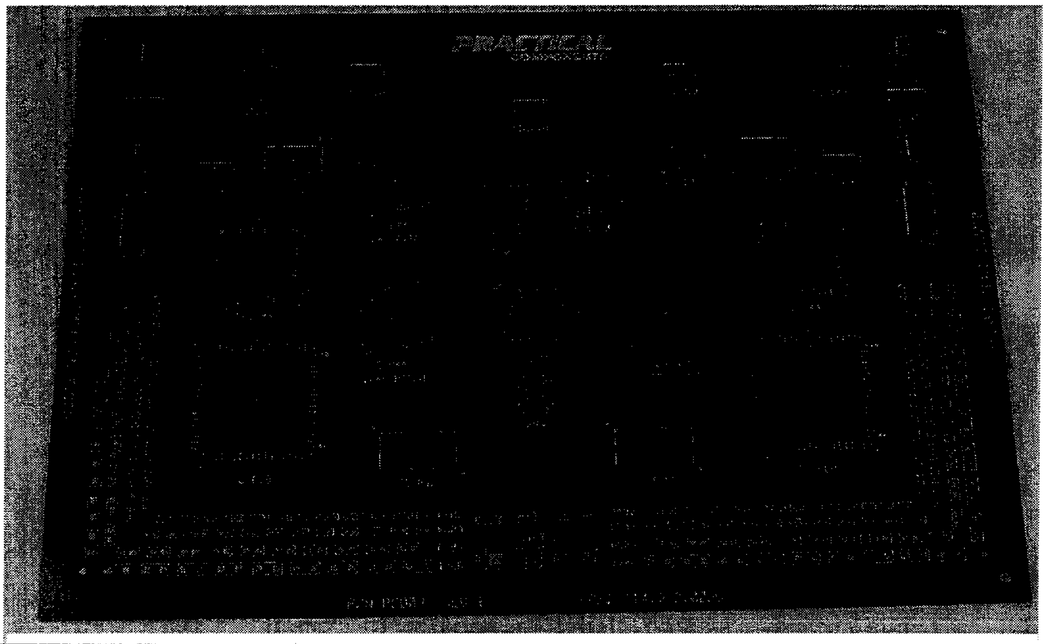


Figure 2: Paste Height Measurement Data



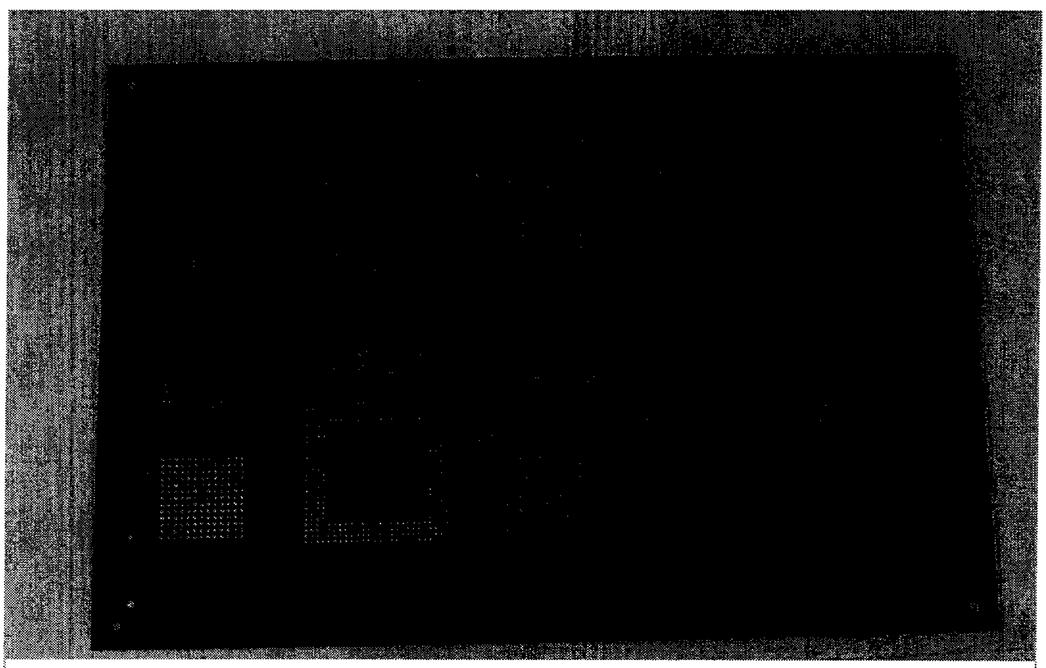
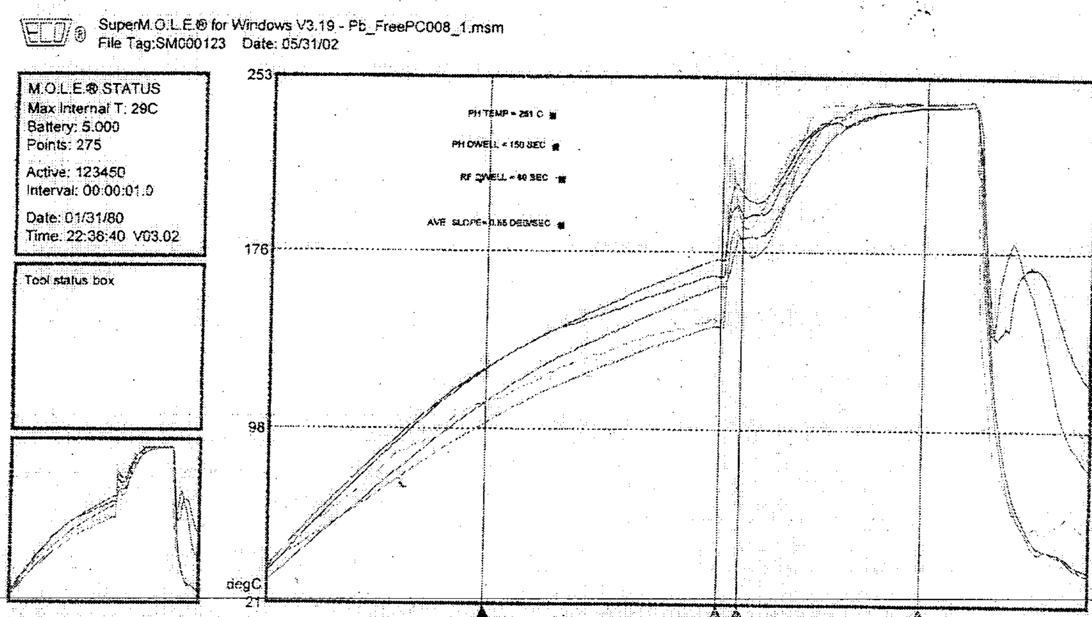


Figure 1: Side 1 and side 2 of test PWB



Value	C1 = 00:01.12r	C2 = 00:02:30r	C3 = 00:02:37r	C4 = 00:03:37r	Units
Sensor 1 Location.	110	161	182	240	degC
Sensor 2 Location.	124	172	201	242	degC
Sensor 3 Location.	124	165	192	240	degC
Sensor 4 Location.	101	143	179	242	degC
Sensor 5 Location.	110	146	185	242	degC
Sensor 6 Location.					

Time To Ref	Low = -18	Med = -18	Hi = -18		Units
Sensor 1 Location.					degC
Sensor 2 Location.					degC
Sensor 3 Location.					degC
Sensor 4 Location.					degC
Sensor 5 Location.					degC
Sensor 6 Location.					

Figure 3: Lead free solder profile

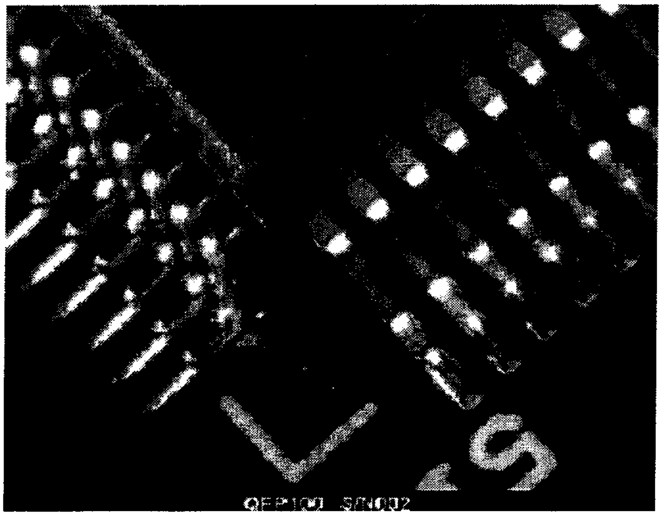


Figure: 7 QFP 100 AFTER REFLOW

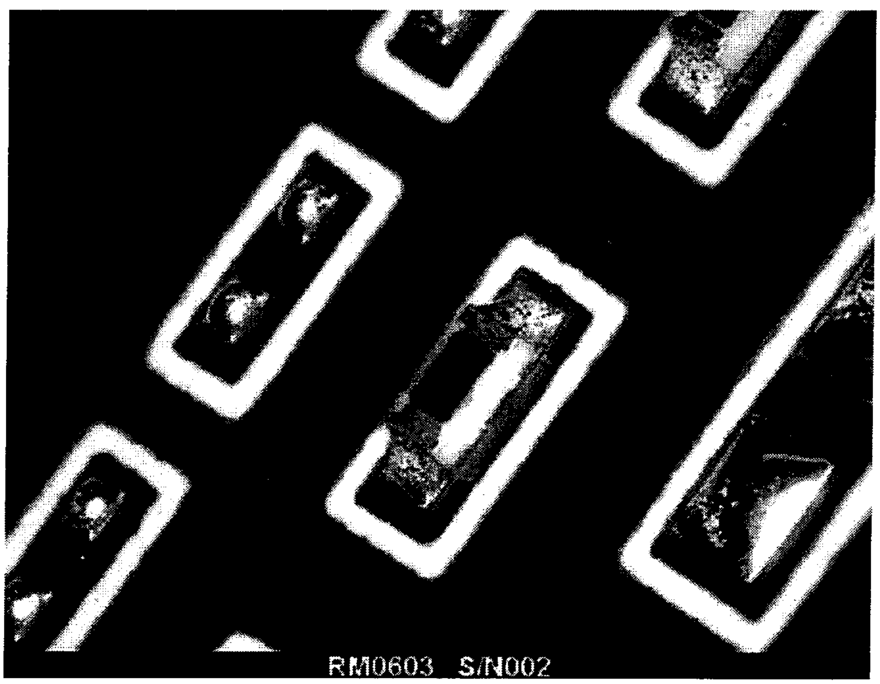


Figure: 8 0603 RESISTOR AFTER REFLOW

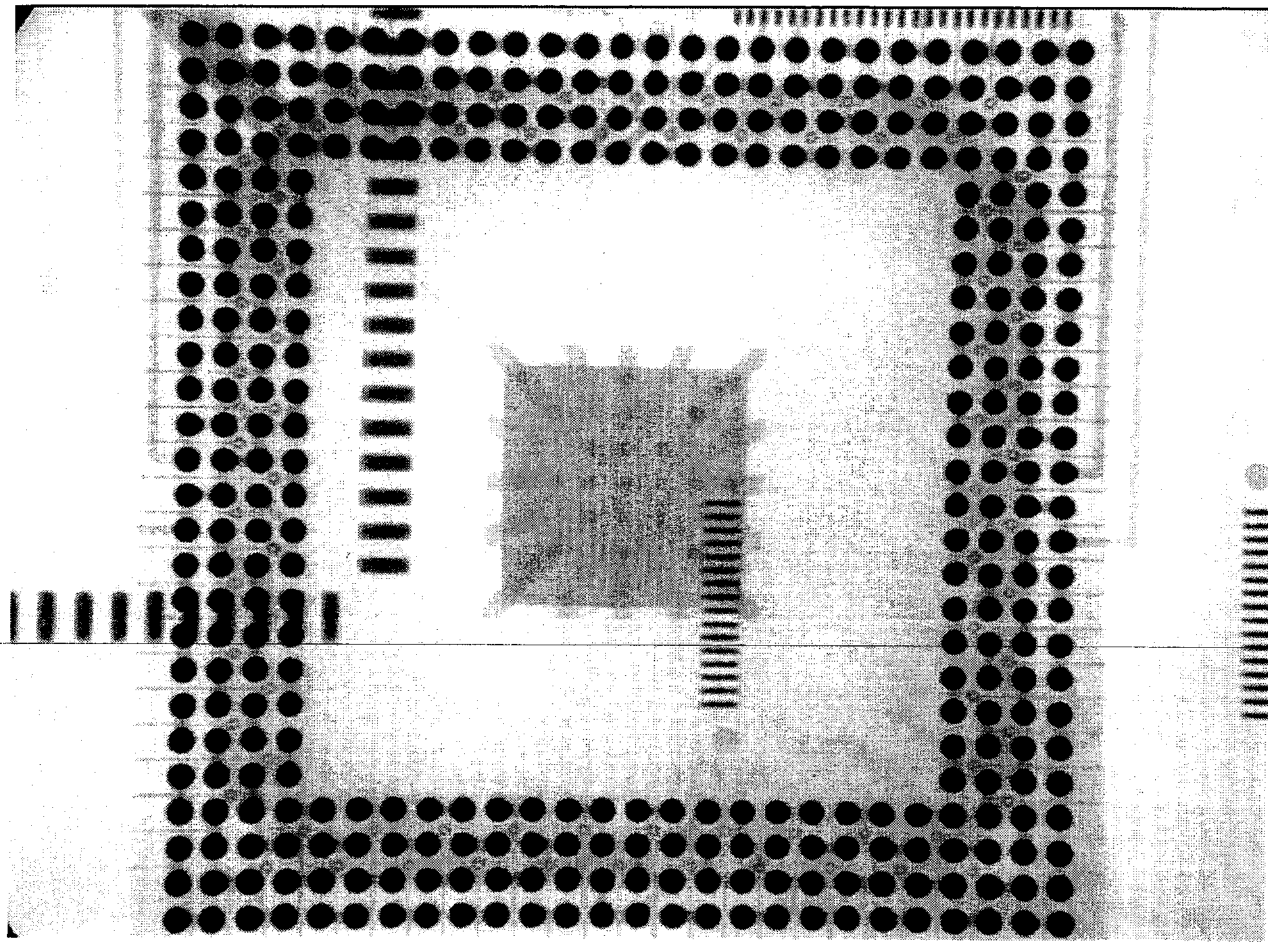


Figure: 4 BGA 352, X-ray Image PWA S/N 001

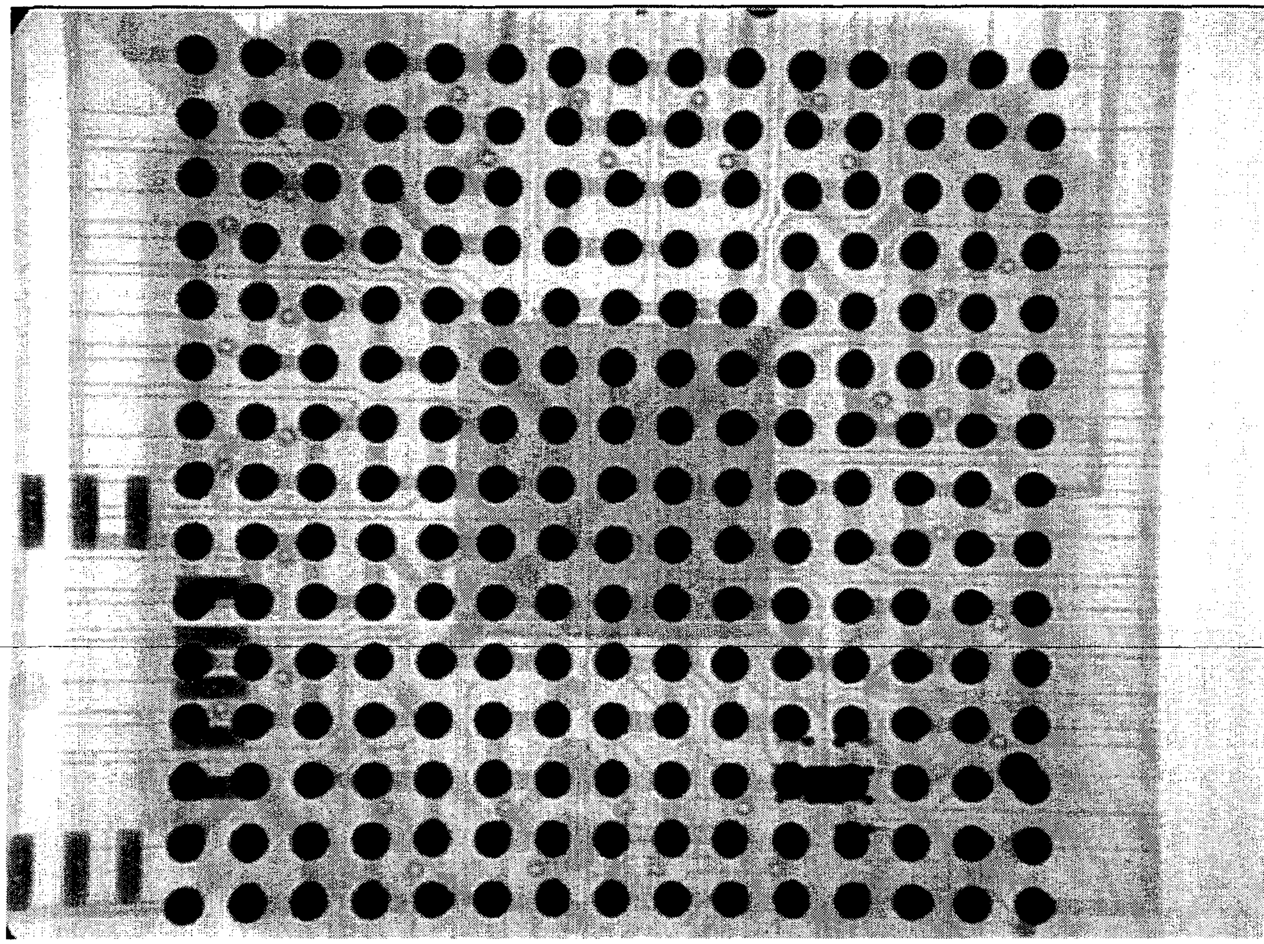


Figure: 5 BGA 225, X-ray Image PWA S/N 001

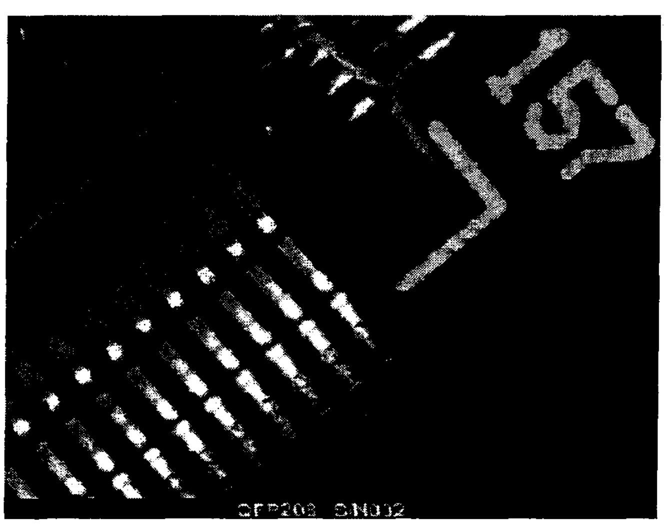


Figure: 6 QFP 208 AFTER REFLOW